

Rocketdyne Automated Dynamics Data Analysis and Management System *

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An automated dynamics data analysis and management system implemented on a DEC VAX minicomputer cluster is described. Multichannel acquisition, FFT analysis, and an online database have significantly improved the analysis of wideband transducer responses from Space Shuttle Main Engine testing. Leakage error correction to recover sinusoid amplitudes and correct for frequency slewing is described. The phase errors caused by FM recorder/playback head misalignment are automatically measured and used by analysis applications to correct the data. Data compression methods are described and compared. The system hardware is described. Applications using the database are introduced, including software for power spectral density, instantaneous time history, amplitude histogram, fatigue analysis, and rotordynamics expert system analysis.

ADDAM SYSTEM DEVELOPMENT

Historically, the analysis of wideband data from Space Shuttle Main Engine (SSME) hot-fire tests has involved a time-consuming manual analysis of power spectral density (PSD) plots, isoplots, root mean square (RMS) time history plots, tracking filter plots, and the like. Manual annotation, comparison, and trend analysis to determine the dynamic characteristics of the hardware under test, assess engine health, and detect anomalous behavior required many hours. More detailed analysis of test responses, such as precise phase correlation, amplitude distribution analysis, and use of instantaneous time histories, was often prohibitively time consuming; these special applications were usually reserved for major anomaly or engine failure investigation.

The requirements of SSME hot-fire test data analysis have expanded since the early test program (1977-1978). Increased test frequency, test duration, number of transducers, and analysis bandwidth have imposed a combined 15-fold increase in processing demand. The extensive tape handling needed to complete the data processing for a typical SSME test resulted in unacceptable delays in test turnaround. The possibility of overlooking early warnings of component failure increased due to the volume of data and limited resource of skilled personnel to evaluate it. A quantum jump in the systems and methods of wideband data processing and analysis was needed.

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Significant advancement has been made at Rocketdyne with the Automated Dynamics Data Analysis and Management (ADDAM) system. ADDAM is an integrated acquisition, digitization, mass storage, and analysis system implemented on a DEC VAX minicomputer cluster. Two multichannel acquisition subsystems, one 16-channel and one 28-channel, can acquire and Fourier transform all data from a single FM tape at wideband data rates up to 256,000 samples per second. All analyses needed to evaluate the behavior of the engine and to diagnose the engine health can be drawn from the digitized data, thus avoiding the multiple handling of the FM tapes. Figure 1 illustrates the simplified processing scheme

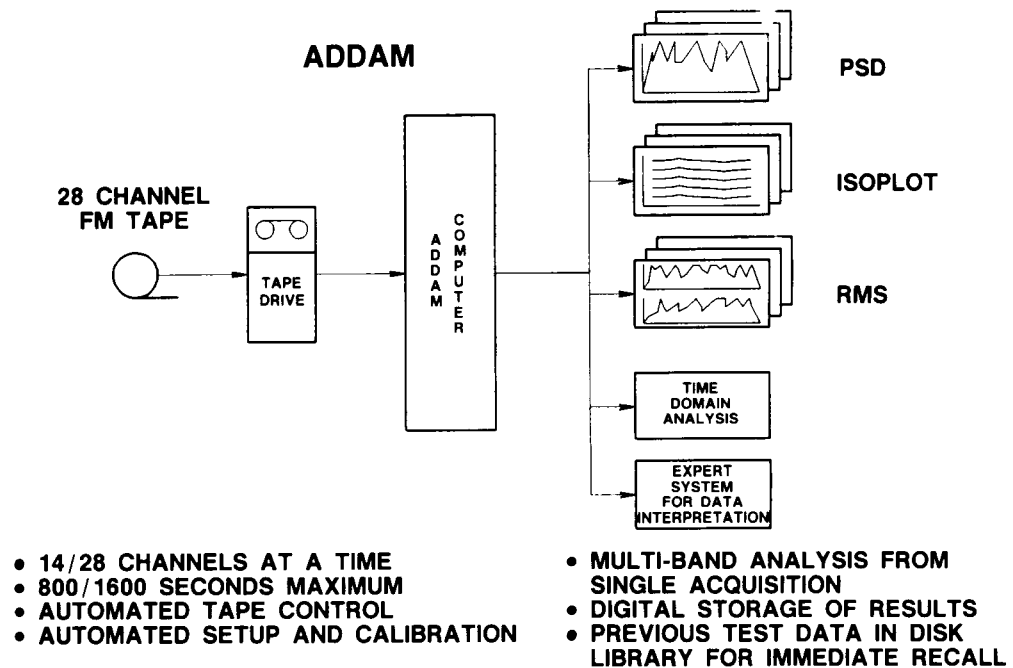


Fig. 1. Multiple Analyses from Single FM Tape Playback

for a typical SSME test. The typical data processing times before, during, and after phase-in of the ADDAM system, since it went online in November 1985, are shown in Fig. 2. This system is now being used to reduce all wideband measurements for entire test durations at a sampling rate of over 10 kHz in real time, an aggregate of over 2 gigabytes (GB) of data for a typical 520-second test. The data storage requirement has been met using state-of-the-art optical disk media. From this raw data base, all standard analyses are drawn, and automation of the manual analysis is underway.

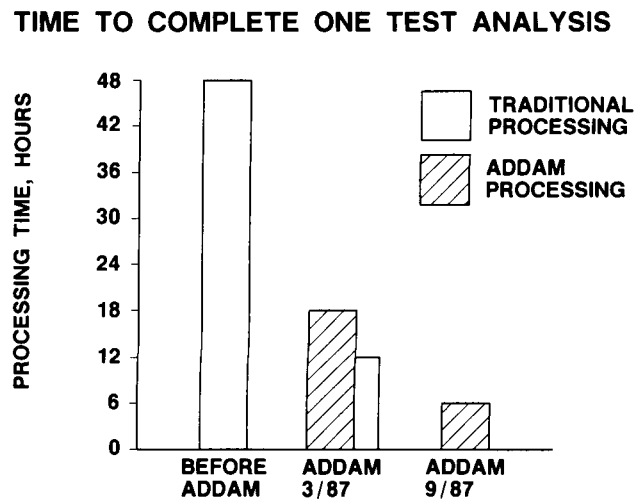


Fig. 2. Reduced Data Processing Using ADDAM

DIGITIZATION CAPABILITIES

To provide a comprehensive and quality database needed for diverse analytical disciplines, the ADDAM system made a number of technical advances. The following describes a few of these.

High Analysis Bandwidth

Many real-time data analysis systems rely on the use of a guard band to minimize alias error. The relatively low rolloff rates of the anti-alias filters of many systems require such caution. The filters employed on the ADDAM system have such sharp rolloff (130 db/octave) that the transition region can be neglected in most cases. As a result, the data of the ADDAM system are often alias free up to the Nyquist frequency. While alias error can occur for a small transition band, the offsetting benefit is increased analysis bandwidth.

Leakage Error Correction

Rectangular windowing is used to permit inverse transformation of the database FFT records. Windowing which ensures that the data sequence is zero at the ends of the sample frame prevents recovery when the FFT is inverse transformed. Leakage occurs when the frequency of a sinusoid does not fall exactly on a multiple of the analysis bandwidth, and is often described as a loss of energy from a primary spectral band into adjacent bands. However, another effect of leakage error is a slewing of the estimate of the frequency, since the FFT analysis can only resolve to within the analysis bandwidth.

Leakage error in the power spectral density is reduced by ADDAM routines using side band integration to estimate the total magnitude of sinusoids, and an amplitude weighted centroid method to more precisely determine their frequencies (Fig. 3):

$$a_c = \sqrt{a_{i-2}^2 + a_{i-1}^2 + a_i^2 + a_{i+1}^2 + a_{i+2}^2} \quad (1)$$

$$f_c = f_i + \Delta f \cdot (a_{i+1} - a_{i-1}) / (a_{i+1} + a_i + a_{i-1}) \quad (2)$$

Table 1 demonstrates the relative error between a leakage-free analysis, a typical case for a sinewave not aligned on an analysis band, and the result of ADDAM leakage error correction. Application of this technique has resulted in elimination of the "chatter" in tracking filter analysis when the actual frequency is between analysis bands.

Phase Correction

Variation in the alignment of the FM tape recorder and playback heads produces large phase errors due to time delays between channels on the FM tape (Fig. 4). These errors have been found to be as large as 120 degrees at 200 Hz. An algorithm was developed [1] to routinely determine these phase errors using analysis of a high-frequency, squarewave calibration signal simultaneously recorded on all channels of a tape. The multiple superharmonics of the squarewave provide the means to determine the channel-to-channel phase errors.

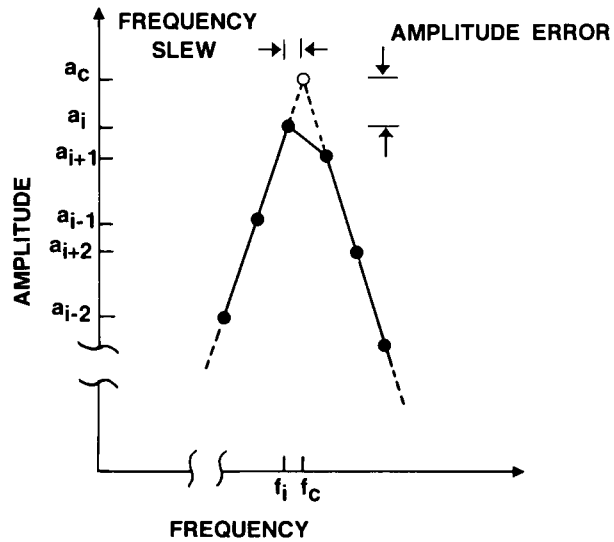


Fig. 3. Leakage Error Correction

Table 1. Leakage Error Correction Data

	NO LEAKAGE	WITH LEAKAGE	LEAKAGE CORRECTION
AMPLITUDE	1.	0.858 (14%)	0.973 (3%)
FREQUENCY, Hz	100.	99.7	99.8

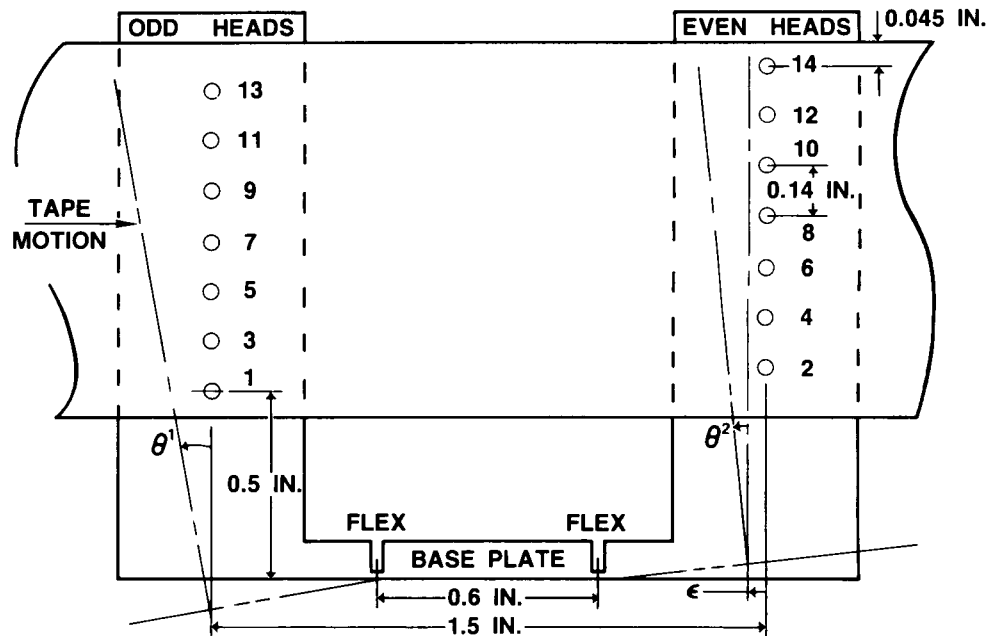


Fig. 4. FM Tape/Head Geometry

The transfer function phase (Fig. 5) at the fundamental and superharmonics of the squarewave is used to obtain an estimate of the phase slope (deg/Hz) of each transfer function. The transfer functions are scanned for points of high coherence using the transfer function phase confidence interval (Fig. 6) defined as [2]:

$$\Delta\phi_{ij} = \arcsin[2/(n-2) * F_{2,n-2;\beta} * (1-\hat{\gamma}_{ij}^2)]^{1/2} \quad (3)$$

where

n = sampling degrees of freedom

β = desired statistical level of confidence

$F_{2,n-2;\beta}$ = 100 β percentage point of an F-distribution for degrees of freedom 2 and $n-2$

$\hat{\gamma}_{ij}^2$ = square of the coherence between the i th and j th channels

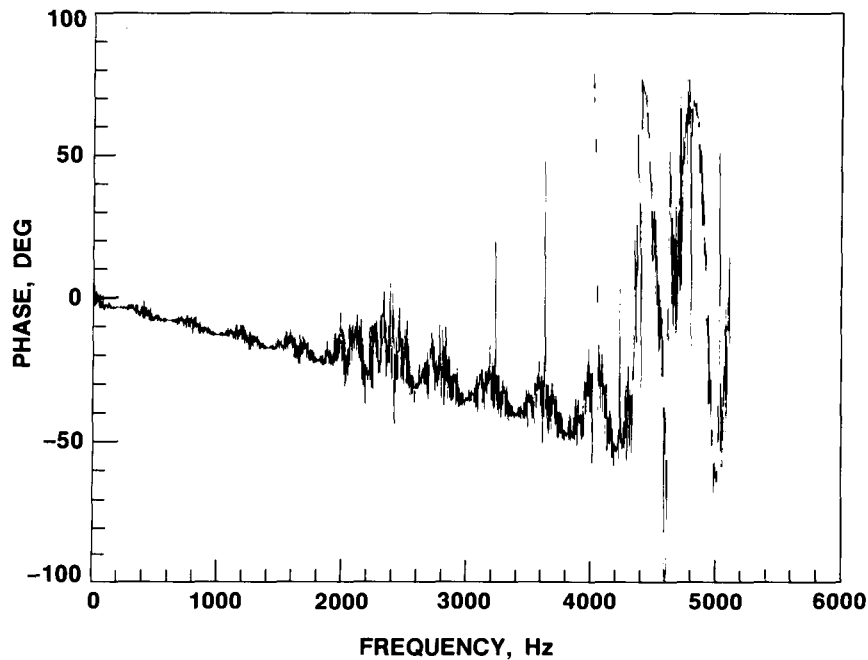


Fig. 5. Phase Calibration Signal Transfer Function Phase

The phase data that pass a tolerance test on $\Delta\phi$ (e.g., 2 degrees) are unwrapped into approximate colinearity and linear regression is then used to determine the phase slope, α , for each transfer function. The transfer function phase can be assumed to have a zero intercept, therefore the linear regression equation becomes

$$\alpha = \sum f_i \phi_i / \sum f_i^2, \quad i=1,m \quad (4)$$

where

m = number of transfer function points used in the linear regression

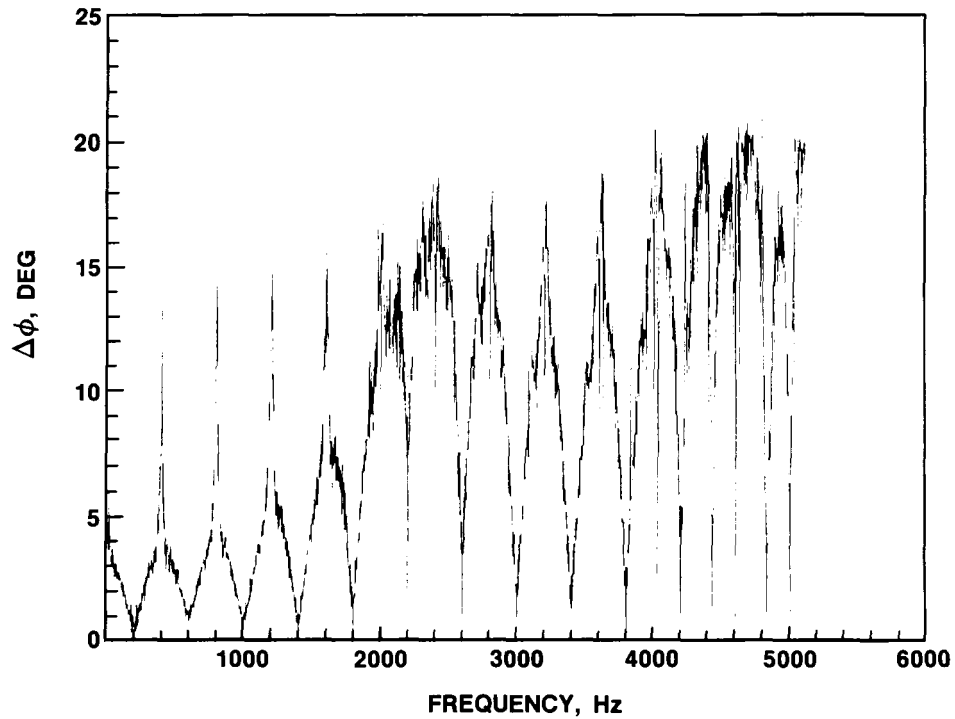


Fig. 6. Transfer Function Phase Confidence Interval

The standard error of regression can be computed using

$$\sigma = [(\sum \phi_i^2 - \alpha \sum f_i \phi_i + \alpha^2 \sum f_i^2) / (m-1)]^{1/2} \quad (5)$$

The phase slope estimates are then improved using the method of least squares to fit them to the model of the tapehead geometry (Fig. 4) given by

$$\begin{aligned} \alpha_{ij}(\theta_1, \theta_2, \epsilon) = & [i * \text{MOD}(i,2) - j * \text{MOD}(j,2)] * \theta_1 \\ & + [i * \text{MOD}(i-1,2) - j * \text{MOD}(j-1,2)] * \theta_2 \\ & + [\text{MOD}(i-1,2) - \text{MOD}(j-1,2)] * \epsilon \end{aligned} \quad (6)$$

where

α_{ij} = phase slope of channel i relative to channel j

Although many combinations of transfer functions may be used in the least-square fit, the best results are obtained by using only the extreme upper and lower channels on the heads. This phase correction method has been tested using data generated with known phase errors, demonstrating that the phase errors are determined to within 0.3 degree at 200 Hz.

The kth element of an FFT vector, R_k , can be corrected to eliminate phase error by complex rotation to R'_k using

$$\phi_k = (1-k) * \alpha \quad (7)$$

$$R'_k = R_k * \exp(\sqrt{-1} * \phi_k) \quad (8)$$

Time history data can be corrected by offsetting the temporal arrays according to the time delay given by

$$\tau = \alpha / (\Delta f * 360) \quad (9)$$

where

Δf = analysis bandwidth

Data Storage Reduction

Data compression methods have been developed and tested. These consist of 16-bit and 12-bit floating point formats and a 16-bit normalized integer format that limit real number precision and dynamic range but substantially reduce storage requirements.

The alternative floating point formats developed for the ADDAM system employ various allotments of bits between the mantissa and the characteristic to achieve reduced storage. Table 2 shows the construction of four floating point formats that have been tested. Type 32 is the VAX 32-bit format (uncompressed). Since floating point numbers can be normalized such that the most significant mantissa bit is set (binary fraction is always greater than or equal to 0.5), this bit is implied in all of these formats.

Table 2. Compressed Floating Point Formats

FORMAT TYPE	CHARACTERISTIC BITS	MANTISSA BITS	MAXIMUM ERROR, %	DYNAMIC RANGE, dB
32	8	23	0.000012	1500
16	8	7	0.78	1500
16-1	5	10	0.098	190
12	5	6	1.5	190

As shown in Table 2, the dynamic range and precision of the resulting compressed number is adequate for most analysis purposes. Type 16-1, with a maximum truncation error of less than 0.1%, is a good combination of reduced storage, adequate dynamic range, and acceptable precision.

For the 16-bit normalized integer format, each component of a block of data is normalized by the block maximum (block scale), then multiplied by 32,767 and converted to integer type. Normalized integer formats are much faster to compress and uncompress, but the relative precision results are very different than with the floating point formats.

The normalized integer format precision is determined by the block scale and the number of "counts" in a signed 16-bit integer (32,767). The amount of relative error varies with the magnitude of the number; near the full-scale

value, the relative error is only 0.003 percent, but for data at 2 percent of full scale the truncation error is 0.15 percent. Dynamic range, however, is not limited since the block scale determines the dynamic range and is stored in full 32-bit floating point format.

HARDWARE DESCRIPTION

A cluster of VAX 11/750 and MicroVAX computers has been created to facilitate control of the simultaneous digitization, database maintenance, analysis, and data transmission tasks required by the integrated ADDAM system (Fig. 7). Functional redundancy of all critical processes is also provided, including CPUs, disk drive capacity, drive controllers, and high-rate data acquisition subsystems.

Automated analysis of test data requires a high efficiency of the front-end process that digitizes signals reproduced from FM tapes, transforms the digitized time histories into Fourier coefficients, and stores the data for use in analysis tasks. The system is flexible with regard to the data acquisition specifications (AC/DC coupling, anti-alias filter frequency, sampling rate, FFT block size, and acquisition start/stop times), and the system completely controls these parameters along with the FM tape operation via digital interface with the host computer.

The anti-alias filter settings are selectable from 10 to 100,000 Hz., and filter rolloff is 130 db/octave. Sampling rates for each channel are selectable from 20 to 500,000 Hz.. Bipolar analog-to-digital converter precision of 15 bits and fixed input sensitivity of 5 volts provides high resolution and overrange free data. FFT processors transform digitized time history points into Fourier coefficients, with a minimum block size of 128 points and maximum block size of 16,384. The FFT processor speed is 0.007 second for a 4096-point block.

The acquisition subsystems include sufficient mass storage to allow them to operate independently of the VAX I/O processors during data acquisition, and are capable of storing digitized time histories for up to 800 seconds of data from 28 channels at a sampling rate of 20,480 Hz. (0.9 gigabytes). Real-time acquisition and FFT transformation are typically performed with a sampling rate of 10,240 Hz and block size of 4096 samples. At higher sampling rates or larger block sizes, the system digitizes the data in real time, and post-processes to perform the FFT calculations.

The acquisition subsystems are also functional as general purpose array processors to perform a wide variety of mathematical functions using data downloaded from the host computers, including inverse FFT transformation, thus greatly increasing the speed and analytical capability of the system.

To interface with the data systems at the Marshall Space Flight Center, the ADDAM system will include communications hardware to transmit over the NASA Program Support Communications Network (PSCN). This link will eliminate the delay of FM tape transmittal between the various test and analysis centers (Fig. 8), thus greatly decreasing the test turnaround time.

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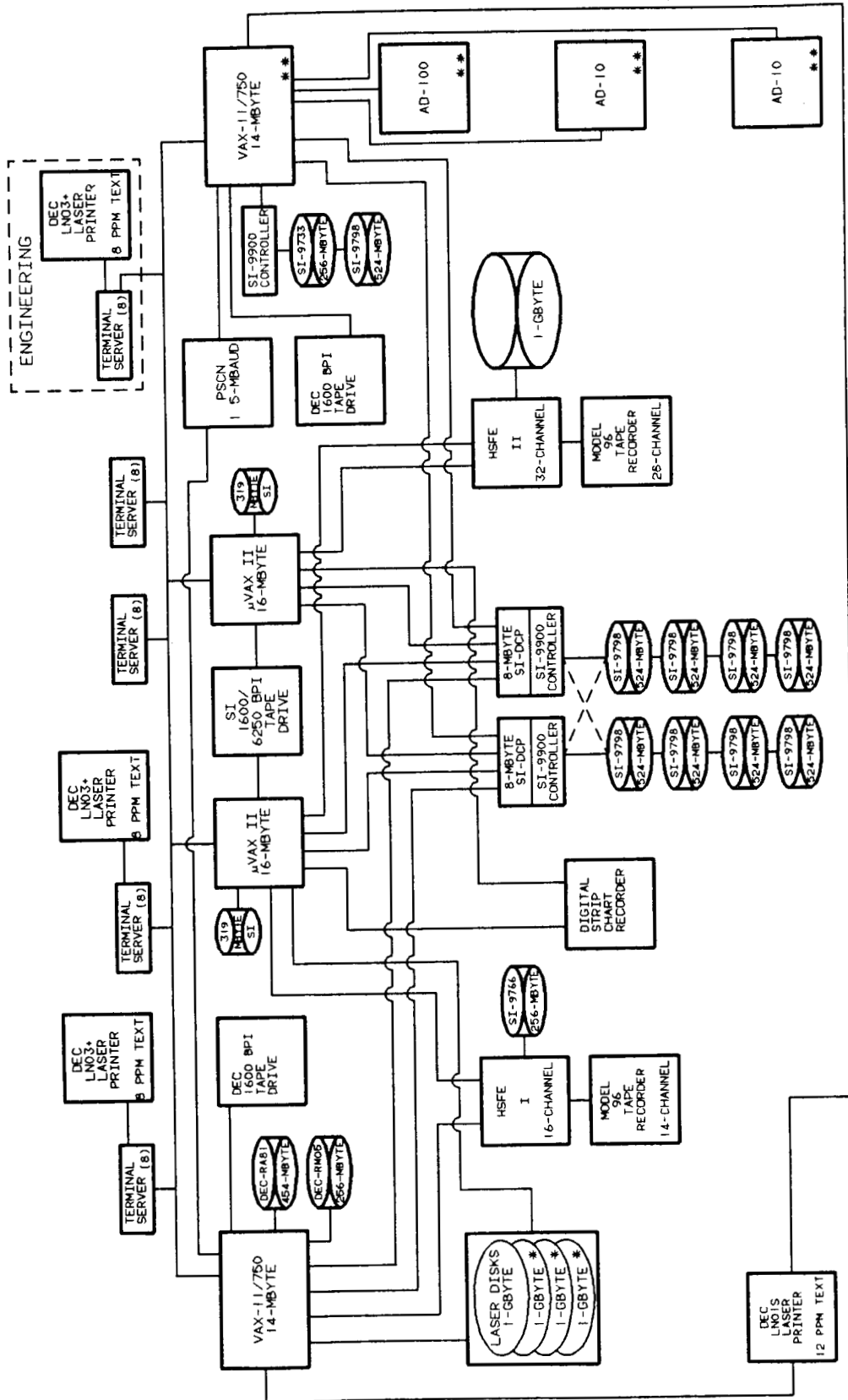


Fig. 7. ADDAM System Schematic

NOTE ALL DISK DRIVES ARE SHOWN WITH FORMATTED CAPACITY.
** ROCKETDYNE HYBRID SIMULATION EQUIPMENT

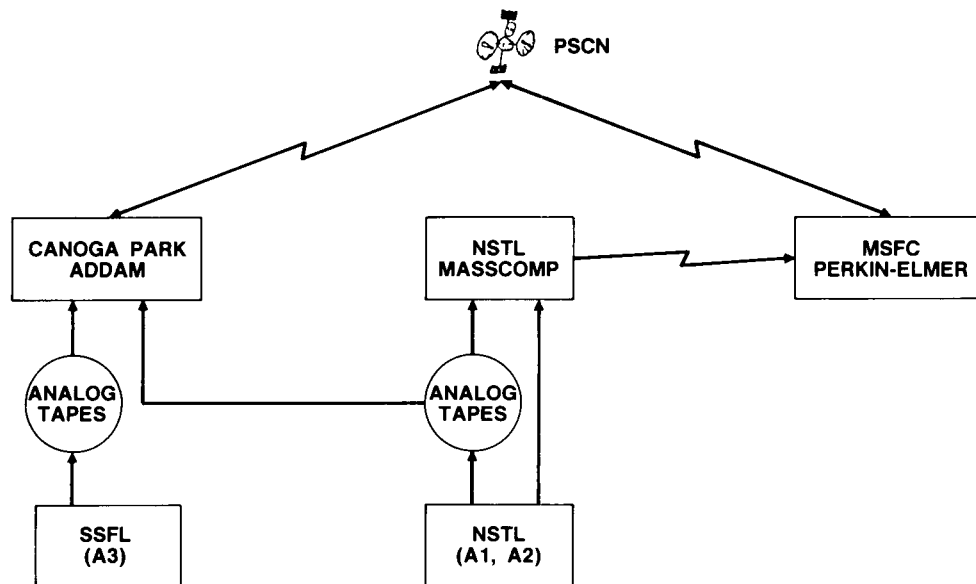


Fig. 8. PSCN Communication Network

QUICKLOOK - ADDAM DATABASE "WORKHORSE"

The standard analyses needed for quick test turnaround are provided by the ADDAM QUICKLOOK program. PSD, RMS time history, isoplot (waterfall plot), amplitude histogram, and instantaneous time history analyses are all available through this program in batch mode or interactively. Examples of these analyses are shown in Fig. 9 and 10.

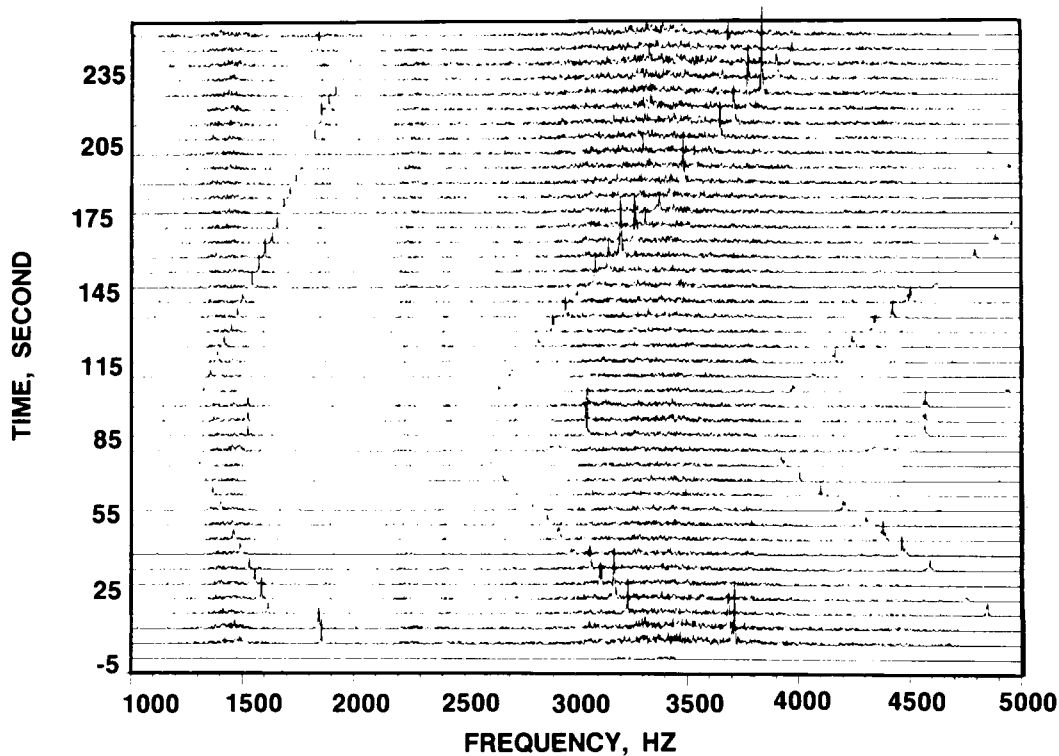


Fig. 9. QUICKLOOK Isoplot Analysis

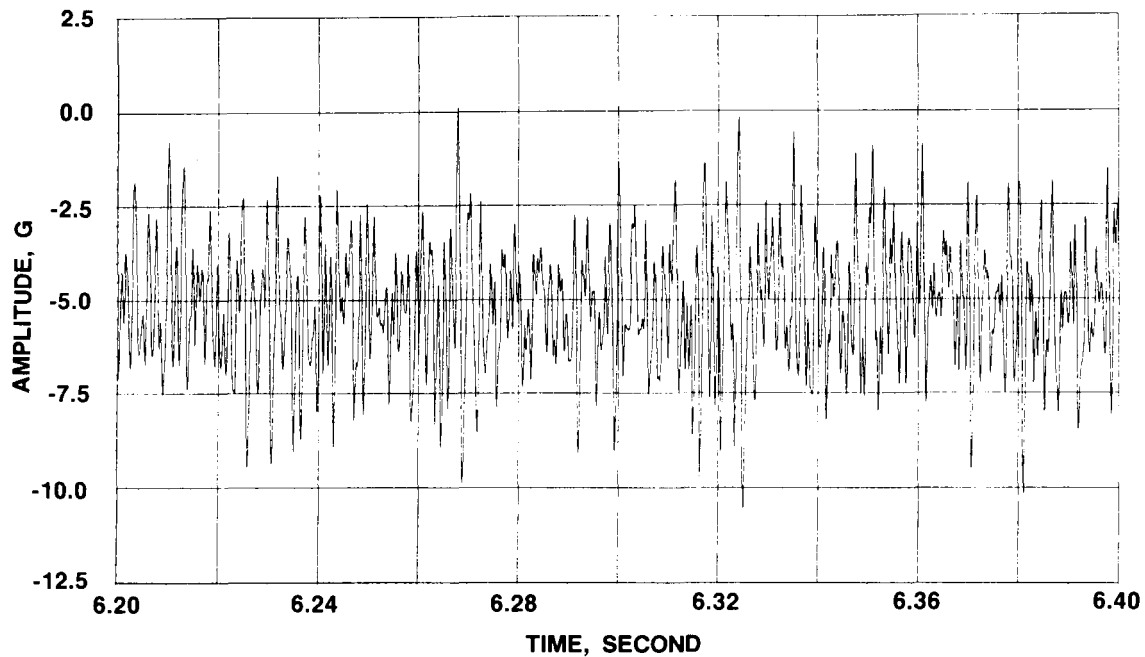


Fig. 10. QUICKLOOK Instantaneous Time-History Analysis

Automation of the system is progressing toward that illustrated in Fig. 11. Batch processing may be requested using an interactive program called REQUEST. The REQUEST program organizes all of the data requirements and en- vokes the data acquisition and analysis systems to perform the necessary func- tions. If data are needed, the ADDAM system issues an operator request to mount the appropriate FM tape. For requests that can be satisfied using data previously digitized and stored, the appropriate archive disk is mounted and the analysis proceeds. Once verified by the expert system and reviewed by an ADDAM database manager, results are delivered back to the requestor.

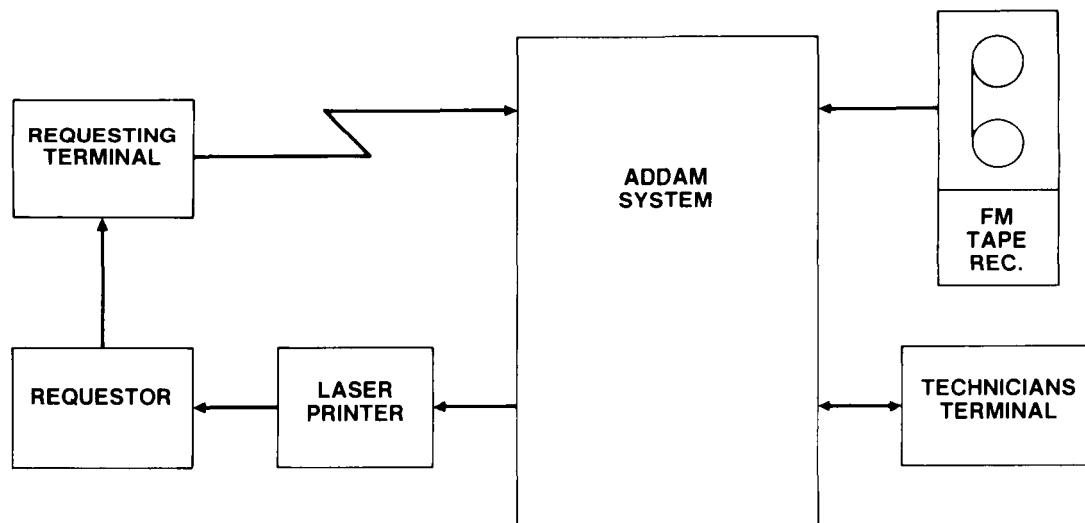


Fig. 11. Data Request Automation

For selected measurements, responses are being statisticized over many tests. The principal independent parameters governing the dynamic responses

have been identified as engine power level, oxidizer and fuel tank pressures, hardware configuration, and preburner mixture ratio. Sample records are currently grouped according to power level for ensemble analysis. The maximum, minimum, mean, and standard deviation of a transducer's ensemble responses are being databased, and will be used in automated data verification and anomaly detection routines. Ensemble maximum (envelope) and mean responses are overlaid with PSDs computed over records of comparable independent parameter conditions (Fig. 12).

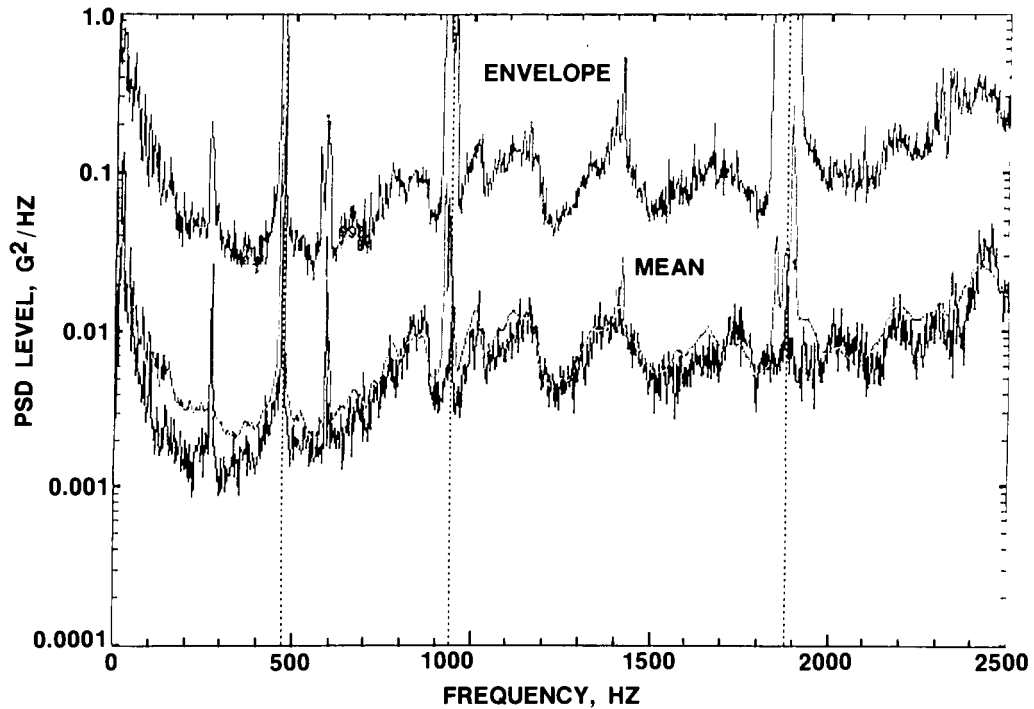


Fig. 12. Envelope Overlay with QUICKLOOK PSD Analysis

INTEGRATED DATA ANALYSIS APPLICATIONS

The ADDAM system has contributed toward significant enhancement of the analytical capabilities of structural and dynamic analysis disciplines at Rocketdyne by providing a reliable source of comprehensive test data. The following are a sampling of analysis applications developed on and made part of the system.

Fatigue Analysis

Rocketdyne's RIDLE and FDAS fatigue life evaluation codes perform analysis in the frequency and time domain, respectively. Using these codes on the ADDAM system, component life can be more realistically and accurately predicted. Fatigue damage analysis, for instance, is now computed using actual time-history responses for entire test durations. This improvement has resulted in life extension for many critical SSME components. Distribution fitting (Fig. 13) is increasing the accuracy of frequency domain methods.

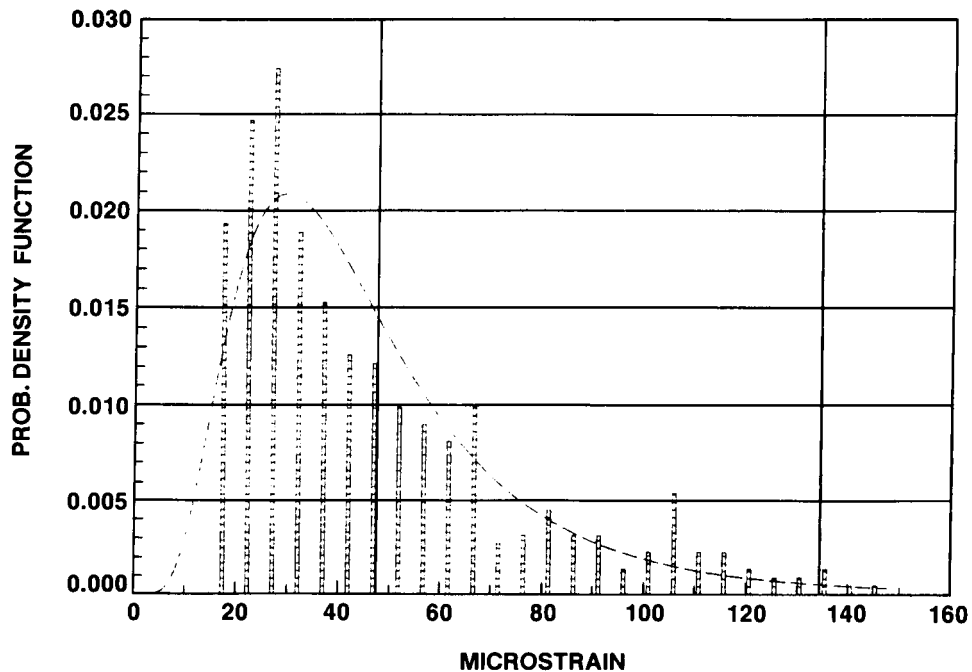


Fig. 13. Probability Density Function and Curve Fit

High-G Impeller Analysis

Hotfire testing of the SSME high pressure oxidizer turbopump (HPOTP) has identified impellers with high synchronous dynamic loads. Using the ADDAM system, analysis is underway to identify the cause of these high dynamic loads. Precise phase correction (± 2 degrees of shaft rotation) is needed to compute bearing load magnitude and phase angle time history from strain gages located on the bearing support structure.

Rotordynamic Expert System

Definition of principal independent variables for the SSME dynamic environment and correlation analysis using multifunctional regression has been used to define the relationships between these independent variables and the engine dynamic environments. A team of experts reviews data from the ADDAM system and identifies "expected events" (indicating the nominal operation of the turbopumps), and "unexpected events" (indicating data of unknown origin, or anomalies). Hypotheses of the source of anomalies are made and tested by various methods. For example, correlation with the statistized ensemble responses, previous test and trends, component test data, computer simulations, and expert experience are used to test the expert system hypotheses.

A prototype expert system (ADDAMX), developed using a rule induction expert system tool called EX-TRAN 7, analyzes rotordynamic data from the low and high pressure fuel and oxidizer turbopumps on the SSME. It is capable of identifying the synchronous vibrations of the rotating machinery, the feed throughs from one turbopump to another, and some critical bearing frequencies. Figure 14 illustrates a PSD analysis processed by the ADDAMX expert system. The plot notation includes frequency, PSD level, and source identification for the sinusoidal components of the signal. The final product is a report on the operation of the turbopumps.

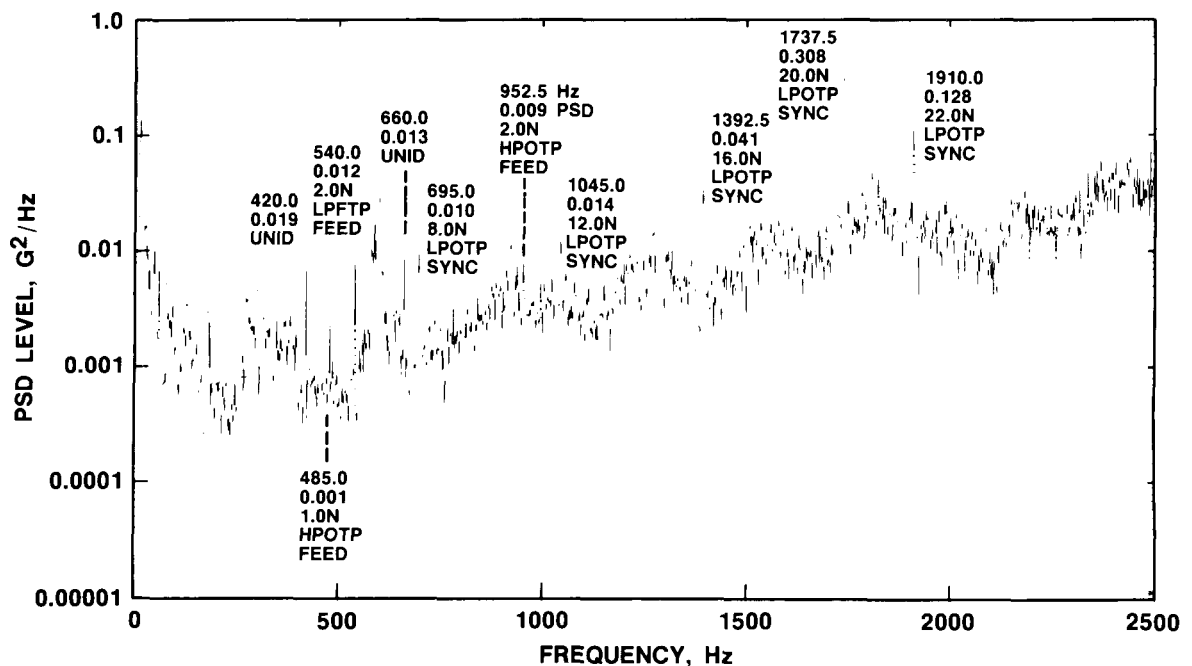


Fig. 14. Rotordynamic Expert System PSD Analysis

CONCLUSION

The ADDAM system has significantly advanced the art of data analysis at Rocketdyne. Since going online in November 1985, the system has dramatically reduced test turnaround time. The database is now comprised of data for the most recent 100 tests, with an aggregate duration of 43,265 seconds. There are 5856 individual measurements, requiring over 55 gigabytes of mass storage, distributed on the system's online magnetic media and archive optical disk media. For any of these data, the expected retrieval time is only a few minutes.

The system's digitization and analysis capability has improved the quality of the data by providing high analysis bandwidth, leakage error correction, and phase error correction. Data storage reduction methods have increased the system storage capacity.

The cluster of VAX computers and peripheral equipment provides an analytical muscle that is supporting improvements in analytical tools used in diverse engineering disciplines. The future development of the expert systems integrated with the database will affect improvements in quality and efficiency at Rocketdyne for years to come.

REFERENCES

1. Rocketdyne internal letter from J. R. Fenwick to J. E. Cusack on 11 April 1986 - Subject: FM Tape Recorded Data Phase Errors and Recommended Calibration Procedures.
2. R. K. Otnes and L. Enochson, Applied Time Series Analysis, Vol. 1, John Wiley and Sons, 1978.